INTEGRATED SYSTEMS

Integrating Cotton and Beef Production to Reduce Water Withdrawal from the Ogallala Aquifer in the Southern High Plains

V. G. Allen,* C. P. Brown, R. Kellison, E. Segarra, T. Wheeler, P. A. Dotray, J. C. Conkwright, C. J. Green, and V. Acosta-Martinez

ABSTRACT

Agriculture in the Texas High Plains depends heavily on irrigation with water withdrawn from the Ogallala aquifer at nonsustainable rates. Our hypothesis was that integrating crop and livestock systems would reduce irrigation water use, maintain profitability, and diversify income compared with a cotton (*Gossypium hirsutum* L.) monoculture. Thus, from 1998 to 2002, two large-scale systems, with three replications in a randomized block design, compared water use, productivity, and economics of (i) a cotton (var 'Paymaster 2326RR') monoculture with terminated wheat (*Triticum aestivum* L.) and (ii) an integrated three-paddock system that included cotton in a two-paddock rotation with grazed wheat and rye (*Secale cereale* L.) and the perennial 'WW-B. Dahl' old world bluestem [*Bothriochloa bladhii* (Retz) S.T. Blake] for grazing and seed production. All paddocks were irrigated by subsurface drip. Angus crossbred beef steers (*Bos taurus* L.; initial body weight = 249 kg; standard deviation = 26 kg) grazed from January to mid-July. During the 4 yr of this experiment following the establishment year, cotton lint yield was 1036 and 1062 kg ha^{-1} for the cotton monoculture and the integrated system, respectively. Bluestem seed yield averaged 24 kg pure live seed ha^{-1}. Steers gained 153 kg on pasture and 0.82 kg d^{-1}. Per hectare, the integrated system used 23% less ($P < 0.001$) irrigation water, 40% less N fertilizer, and fewer other chemical inputs than the cotton monoculture. Profitability was about 90% greater for the integrated system at described conditions. Integrated production systems that are less dependent on irrigation and chemical inputs appear possible while improving profitability.

CROP PRODUCTION on the Texas High Plains has used supplemental irrigation with water pumped from the Ogallala aquifer at rates that have far exceeded recharge for many years. Water from the Ogallala will not be available in the future to sustain irrigated agriculture in this region as it has during the past 50 yr, and adoption of water conservation strategies is imperative. About 20 to 25% of the total U.S. cotton crop is produced in this region with more than 1.5 million ha

planted annually, primarily in monoculture systems (TASS, 2002). Furthermore, about 5.5 million stocker cattle (about 25% of U.S. total; TASS, 2002; USDA Natl. Agric. Stat. Serv., 2003) are shipped into the High Plains each autumn to eventually enter area feedyards, but other than grazing wheat before grain harvest, little integration of livestock and crop production exists.

Integrated crop–livestock systems can improve soil quality, interrupt pest cycles, and spread economic risk through diversification (Krall and Schuman, 1996), but research is limited. Integrated crop and livestock systems in Australia that included legume pastures improved soil quality and reversed a decline in wheat yields (Donald, 1981). Luna et al. (1994) described whole-farm system comparisons for integrated crop and livestock production in Virginia. In these system comparisons, integrating grazing into a 4-yr corn (*Zea mays* L.)–alfalfa (*Medicago sativa* L.) rotation increased steer gains, reduced N and pesticide use, and maintained profitability compared with the nonintegrated system (J.P. Fontenot et al., Virginia Tech, Blacksburg, unpublished data, 2000). Krall and Schuman (1996) suggested that integrated dryland crop and livestock production systems on the Great Plains represent an ecologically and economically sustainable form of agriculture but are agriclimatic zone specific. In the Southern High Plains of West Texas, virtually no published information exists for integrating animal agriculture into irrigated crop production.

In 1997, a multidisciplinary team of people representing academics, practitioners, agricultural industries, government agencies, and local businesses designed research to reduce dependence on irrigation while maintaining or improving profitability. Our hypothesis was that viable grazing systems could be developed and integration of crops, forage, and livestock in production systems would reduce use of water while maintaining appropriate levels of crop and livestock production and profitability. Thus, objectives of this research were to compare productivity, profitability, and impact on water use of (i) a cotton monoculture system managed by best management practices for the area and (ii) an integrated cotton–forage–livestock system. This long-term project continues, but results of the first 5 yr are presented here.

MATERIALS AND METHODS

Research was initiated in 1997 to compare a continuous cotton monoculture system with an integrated cotton–forage–

V.G. Allen, C.P. Brown, and C.J. Green, Dep. of Plant and Soil Sci., Texas Tech Univ., Lubbock, TX 79409-2122; R. Kellison, Silver Creek Farm, Lockney, TX 79241; E. Segarra, Dep. of Agric. and Appl. Econ., Texas Tech Univ., Lubbock, TX 79409; T. Wheeler, Texas A&M Agric. Exp. Stn., Lubbock, TX 79403; P. Dotray, Dep. of Plant and Soil Sci., Texas Tech Univ., Lubbock, TX 79409-2122 and Texas Cooperative Extension, Lubbock, TX 79403; J.C. Conkwright, High Plains Underground Water Conservation District No. 1, Lubbock, TX 79411-2499; and V. Acosta-Martinez, USDA-ARS, Lubbock, TX 79415. Approved by the Dean of the College of Agriculture and Natural Resources, Texas Tech Univ. Publ. no. T-4-555. Received 18 May 2004. *Corresponding author (felician@ttu.edu).
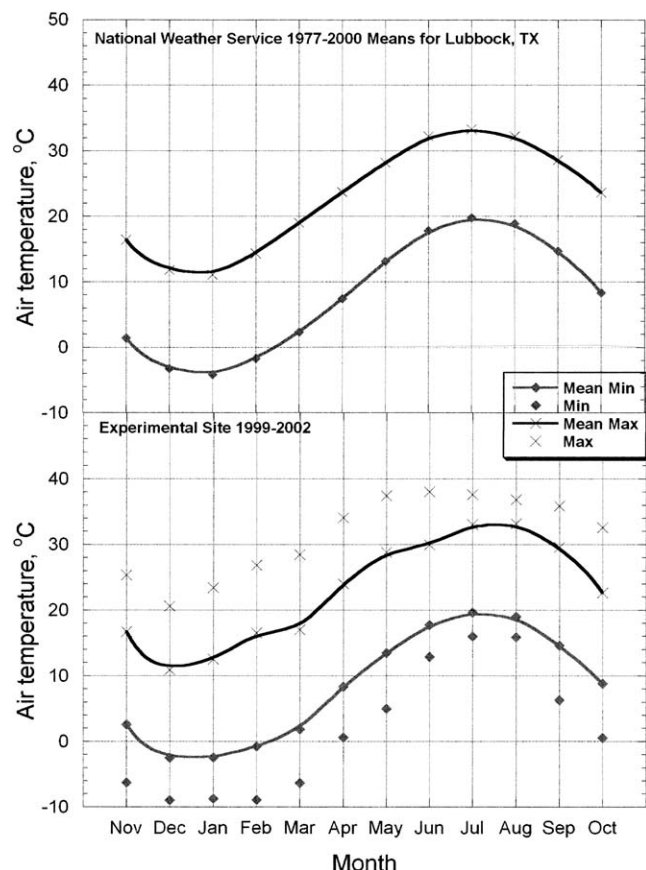
Fig. 1. Minimum and maximum temperatures during 5 yr at site of comparison of a cotton monoculture and an integrated cotton, forage, and livestock system and the long-term average (1977–2000) for Lubbock, TX (about 16 km from research site).
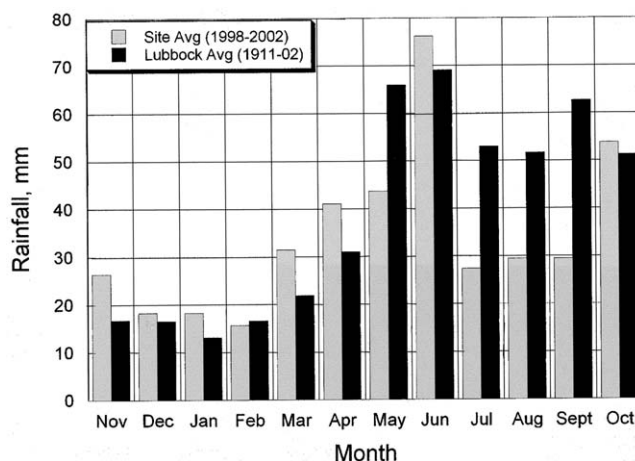

Fig. 2. Precipitation during 5 yr at site of comparison of a cotton monoculture and an integrated cotton–forage–livestock system and the long-term average (1911–2002) for Lubbock, TX (about 16 km from research site).

livestock system. The research site was located in northeast Lubbock County, a part of the Llano Estacado of the Southern High Plains (33°45′ N, 101°47′ W; 993 m elevation). The landscape is characterized by nearly level soils with 0 to 1% slopes. Soils were primarily Pullman clay (fine, mixed, superactive, thermic Torrertic Paleustolls) characterized by a thick layer of $CaCO_3$ (caliche) at varying depths throughout the region that limits root penetration (Brooks et al., 2000). The research area was defined by a dry steppe climate and mild winters typical of this region (Fig. 1). Mean long-term (1911–2002) annual precipitation is 470 mm with about 75% of precipitation occurring from April through October (Fig. 2). About two-thirds of annual rainfall occurs just before or during the growing season. Weather data including precipitation, wind speed and direction, relative humidity, solar radiation, and temperature were recorded every 15 min and averaged hourly at the site by a Campbell Scientific 21X micrologger weather monitoring station (Campbell Scientific, Inc., Logan, UT). Percentage of evapotranspiration was calculated as a percentage of reference crop evapotranspiration (ET_o; Allen et al., 1998) and modified according to the ASCE Standardized Reference Evapotranspiration Equation (EWRI, 2001).

Each system was replicated three times in a complete randomized block design. Each replication in the monoculture cotton system included 0.25 ha, and each replication of the integrated crop–livestock system comprised 4 ha for a total of 12.75 ha in the experimental area. Establishment for both systems began in 1997. Year 1 of data collection for crop components for both systems began in 1998 with cattle entering the system in 1999. Year 5 was completed in 2002 with 5 yr

of crop data and 4 yr of cattle data. A year was arbitrarily considered to occur between 1 November and 31 October because this period of time was annually inclusive of most plant and animal production cycles except for Year 1, which included more than 12 mo in the establishment phase but was considered to end 31 Oct. 1998.

Both systems were irrigated by an underground drip system (Netafim, Tel Aviv, Israel) with each individual paddock equipped with a turbine water meter (Master Meter WNT-01, Fort Worth, TX) to measure total water applied. Drip tapes on 1-m centers and about 0.36 m deep with injection emitters on 0.6-m centers were used to deliver 1.47 L h^{-1} at 88.3 kPa. Irrigation capacity was 2.5 mm h^{-1}, and variable volumes could be applied daily depending on crop water demands. Total water supply to each cropping sequence was determined using rain gauges, located at three points across the experimental site, for natural precipitation and meters, described above, for measurement of irrigation water. In 1998 and 2001, soil moisture was determined gravimetrically at planting within each replication of cotton for both systems. Sampling depths were at 30-cm intervals to a depth of 120 cm in 1998 and were 0- to 5-, 5- to 10-, and then 10-cm intervals to a depth of 60 cm in 2001.

For each system, application of fertilizers was based on soil test results and yield goals and pesticides on recommendations of integrated pest management specialists. Inputs of water, fertilizers, pesticides, seeds, labor, and mechanical inputs were recorded. All fertilizer applications were made through the drip irrigation system. All herbicide applications were made using TeeJet 8002 flat fan nozzles calibrated to deliver 122 L ha^{-1} at 379.5 kPa.

Cotton Monoculture System

This system consisted of a single paddock (100% of system; replicated three times) for monoculture cotton planted into terminated wheat (Fig. 3). Cattle were not a part of this system. Soil was listed on 1-m centers over drip irrigation tapes. 'Lockett' wheat at 56 kg ha^{-1} was planted in three 18-cm rows in furrow bottoms between listed rows each autumn following cotton harvest. Nitrogen (67 kg ha^{-1}) was applied through the irrigation system in late winter (mean date 22 February). In spring, wheat was chemically terminated with glyphosate [N-(phosphonomethyl)glycine] (Monsanto, St. Louis, MO) at 0.84 kg a.i. ha^{-1}. Paymaster 2326RR cotton was planted (194 000 seed
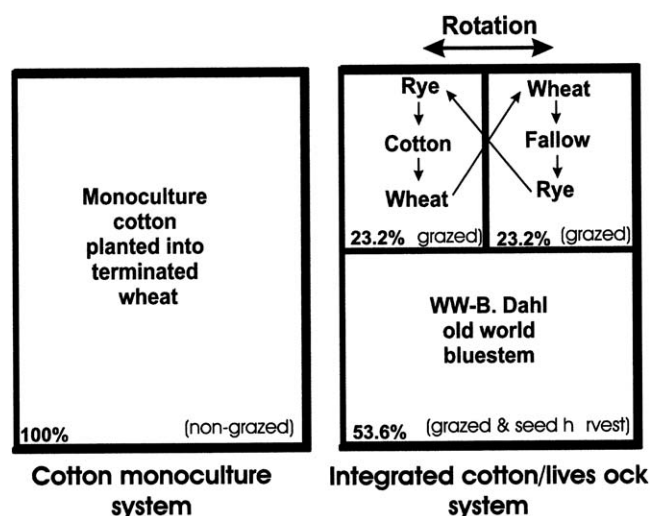
Fig. 3. System design for a cotton monoculture and an integrated cotton–forage–livestock system.

ha⁻¹) in mid-May each year (mean planting date 15 May) into tops of listed rows. Chemicals applied during the 5 yr are listed in Table 1. Four applications of N were made to cotton during the growing season at various stages of development.

Cotton was harvested with a four-row cotton stripper in autumn (mean harvest date 15 November). Total weight of harvested cotton, seed, and trash was obtained by replication in the field at time of harvest by weighing the entire harvested crop in a boll buggy equipped with load cells. Harvested cotton was ginned commercially by field replication, and percentages of lint and seed were determined by the cotton gin. Subsamples of cotton lint for each replication were tested for color, micronaire, length, strength, and uniformity by the Texas Tech

University International Textile Center, Lubbock. Immediately following cotton harvest, wheat was drilled into furrow bottoms between listed rows.

Integrated Cotton–Livestock System

About 53.6% of the total system replication land area (2.1 ha) was established in the perennial warm-season grass WW-B. Dahl old world bluestem (Fig. 3). Seed [3.4 kg pure live seed (PLS) ha⁻¹] was planted into a prepared seedbed with a Horizon grass drill equipped for handling fluffy seed. In early August each year, 67 kg N ha⁻¹ was applied through the irrigation system. This grass provided grazing intermittently for steers from January to July and a seed crop in October. Seed were commercially harvested, cleaned, and tested for percentage PLS.

The remaining 46.4% of this system was divided into two equal-sized paddocks of 0.93 ha each. Cotton was grown in alternate rotation between these two paddocks. 'Maton' rye was planted (112 kg ha⁻¹) in early September of each year before cotton. At planting, 67 kg N ha⁻¹ was applied through the irrigation system. Beginning in January, steers grazed rye in sequence with old world bluestem as growth of rye permitted until early April. Cattle were then excluded from rye, regrowth of rye was terminated by applying glyphosate as described previously, and Paymaster 2326RR cotton was no-till planted in mid-May (mean planting date 15 May) as described previously. Chemicals used are presented in Table 1. Nitrogen was applied to cotton as described for the monoculture system. Cotton was harvested in November (mean harvest date 15 November). Yield was measured, and samples for quality analysis were collected as described above.

Immediately following cotton harvest each autumn, Lockett wheat was planted (112 kg ha⁻¹) into cotton stalk stubble with a no-till Tye stubble drill (AGCO, Lockney, TX). Nitrogen

Table 1. Chemical inputs to a cotton monoculture and an integrated cotton–forage–livestock system averaged over 5 yr.

	System components (% of system)						
	Monoculture			**Integrated**			
Item, unit	Cotton (100.0)	Wheat (100.0)	Total (100.0)†	Cotton (23.2)	Wheat/rye (23.2)	OWB‡ (53.6)	Total (100.0)†
	amount a.i. ha⁻¹						
Herbicides							
Metsulfuron-methyl, g	0.0	0.0	0.0	0.0	0.0	0.8§	0.4
Dicamba, g	0.0	22.4	22.4	0.0	22.4	0.0	5.2
Glyphosate, kg	2.9	0.4	3.4	2.6	2.2	0.0	1.1
Fluazifop-P, g	37.0	0.0	37.0	37.0	0.0	0.0	8.6
S-metolachlor, g	0.0	0.0	0.0	347.6§	0.0	0.0	80.6
Prometryn, g	0.0	0.0	0.0	336.0§	0.0	0.0	77.9
Trifluralin, kg	1.0	0.0	1.3	0.0	0.0	0.0	0.0
Insecticides							
Aldicarb, g	588.0	0.0	588.0	588.8	0.0	0.0	136.4
Lambda-c, g	43.2	0.0	43.2	43.2	0.0	0.0	10.0
Dicrotophos, g	112.0	0.0	112.0	112.0	0.0	0.0	26.0
Chlorfenapyr, g	57.1	0.0	57.1	57.1	0.0	0.0	13.3
Methyl parathion, g	84.0	0.0	84.0	84.0	0.0	0.0	19.5
Acephate, g	25.2	0.0	25.2	25.2	0.0	0.0	5.8
Thiamethoxam, g	7.0	0.0	7.0	7.0	0.0	0.0	1.6
Growth regulators and defoliants							
Mepiquat-Cl, g	20.8	0.0	20.8	28.2	0.0	0.0	6.5
Tebufenozide, g	35.0	0.0	35.0	35.0	0.0	0.0	8.1
Tribufos, g	168.0	0.0	168.0	168.0	0.0	0.0	39.0
Diuron, g	7.0	0.0	7.0	7.0	0.0	0.0	1.6
Thidiazuron, g	14.0	0.0	14.0	14.0	0.0	0.0	3.2
Ethephon, kg	1.4	0.0	1.4	1.4	0.0	0.0	0.3
Fertilizer N							
kg ha⁻¹	125.0	27.0	152.0	128.0	119.0	65.0	96.0¶
% of total applied	82.2	17.8	100.0	30.9	28.8	36.9	100.0

† Mean is calculated based on the percentage contribution of each system component.
‡ OWB, 'WW-B. Dahl' Old World bluestem [*Bothriochloa bladhii* (Retz) S. T. Blake].
§ Required only in Year 1 during establishment.
¶ Includes 67 kg ha⁻¹ applied to sorghum in Year 1 only (data not shown).

(67 kg ha^{-1}) was applied though the irrigation system in late winter (mean date 22 February). Wheat was grazed by steers after rye grazing was terminated. Following graze-out of wheat, land was fallowed until rye was planted in September. This paddock was sprayed with glyphosate to terminate weeds and was clipped at least once to control volunteer cotton. Thus, because there were two paddocks in rotation, cotton alternated each year between paddocks, and both rye and wheat were available for grazing in sequence each winter (rye) and spring (wheat). In the establishment year only, 'Pioneer 842F' sorghum [*Sorghum bicolor* (L.) Moench] was planted 15 July (43 kg ha^{-1}) following graze-out of wheat.

Twenty-one Angus and Angus × Hereford steers (average initial body weight = 249 kg; standard deviation (SD) = 26 kg) were purchased through stocker calf sales each winter. Steers were vaccinated on arrival with *Clostridium Chauvoei-Septicum-Novyi-Sordellii-Perfringens* Type C & D *Bacterin-*Toxoid (Fortress 7, Pfizer Animal Health New York, NY), infectious bovine rhinotracheitis, parainfluenza 3 virus, bovine viral diarrhea, and bovine respiratory syncytial virus (Bova-Shield 4, Pfizer Animal Health, New York, NY) and were treated for internal parasites with Dectomax (Pfizer Animal Health, New York, NY). Steers were also implanted with Ralgro (Schering-Plough Animal Health Corp., Union, NJ) initially and at 90-d intervals. Steers were weighed on arrival following an overnight shrink and were blocked by weight and randomized to the three replications for the system (seven steers/rep). Averaged across 4 yr, grazing began on 6 January and ended on 16 July when steers went to the feedyard. Steers were weighed initially and every 28 d throughout the grazing season and at the end of the grazing season. Plain salt was provided ad libitum, and a 41% crude protein (CP) cotton-seed cake (Purina Mills, St. Louis, MO) was supplemented to meet CP requirements (Natl. Res. Counc., 1996) at about 0.7 kg steer^{-1} d^{-1} while steers primarily grazed dormant old world bluestem. Crude protein supplementation was discontinued once grazing was dominated by small grains or spring growth of bluestem. Steers were handled under an Animal Care and Use Protocol approved by the Texas Tech University Animal Care and Use Committee.

During winter, steers grazed primarily stockpiled dormant old world bluestem. Stockpiled forage represented growth accumulated from the time steers left pastures in mid-July. Steers sequence-grazed rye first and later wheat as available but were continuously stocked during the time they grazed each individual forage. Stocking densities for old world bluestem and small-grain paddocks were 3.3 and 7.5 steers ha^{-1}, respectively. Stocking rate for the overall system was 1.75 steers ha^{-1}. Steer grazing days per hectare were calculated as: [(number of days grazed) × (number of steers)/(paddock size, ha)]. Steer grazing days per hectare per centimeter of irrigation water applied was calculated as: [(steer grazing days per hectare)/(irrigation water, cm)].

Steers and forages were managed separately by replicate such that they moved from one system component to another based on forage growth for that replication. Little difference in grazing management, however, was required among replicates. By mid-July, steers were moved to a commercial feedyard for finishing but were considered "sold" at the end of the pasture phase. At the end of the finishing phase, final live weights were taken immediately before harvest, and USDA Quality Grades were collected after harvest.

Soil-Borne Diseases

Soils were assayed for *Verticillium* wilt (*Verticillium dahliae* Kleb.) (Wheeler and Rowe, 1995) and nematodes (Thistle-thwayte, 1970) and bioassayed (Wheeler et al., 2000) for seedling diseases of cotton and wheat. Field observations were made for seedling disease and wilt symptoms. Within the integrated cotton–livestock system, three samples were taken from each replication of perennial paddocks, and two samples were collected from each of the two paddocks in the cotton–small-grain rotation. For the cotton monoculture system, one sample was collected from each replication.

Weed Populations and Control

Baseline weed populations were determined using three 8.1- by 9.1-m subplots per plot. Weeds were identified using common and scientific names approved by the Weed Science Society of America and recorded. In subsequent years, weeds were monitored visually for weed control recommendations provided by Texas Cooperative Extension, Lubbock.

Economic Analysis

Detailed records of input use and tillage operations were used to develop cost and return budgets for components in both production systems. Cost of production portion of these budgets was composed of variable costs and fixed costs. Variable costs accounted for the cost of all preharvest and harvest inputs used and capital costs associated with use of these inputs. Irrigation system–related charges assumed installation of a subsurface irrigation system for a representative 50-ha irrigated farm in the Texas High Plains. Due to farm-to-farm variability of pumping-lift in the Texas High Plains, four common pumping lifts were used (45, 60, 75, and 90 m). Actual pumping depth at the research site was 90 m. Because benefits received by producers vary among farms, net returns do not include any government payments. Year 1 is presented separately because this year did not include cattle.

Statistical Analysis

Although differences existed in total land area between the two systems, they were compared on an equal land equivalent basis using percentages that each system component comprised to calculate outcomes. Thus, the monoculture system comprised 100% per unit land area for this system while the same unit land area for the integrated system was made up of 53.6% perennial pasture and the two paddocks in rotation for cotton and small grains each comprised 23.2% of the system (Fig. 3). In any given year, cotton accounted for 23.2% of land area in the integrated system. Data were analyzed as a randomized block design using a model that tested effects of system, block, and year and system × year interaction (Steel and Torrie, 1960). Where appropriate, effects of crops within systems were further tested with mean separation by a protected LSD test.

RESULTS AND DISCUSSION

Climate

Average temperature during the 5 yr of this experiment generally followed long-term means (Fig. 1), but temperatures during the establishment year were higher than the long-term average for this region (data not shown). Precipitation was higher during November, March, April, and June and was lower during May, July, August, and September than long-term means (Fig. 2). Total annual mean precipitation at the site was 446 mm for the 4 yr following establishment compared with the

470-mm long-term (years 1911 through 2002) regional average. In Year 1, the establishment phase, only 292 mm of precipitation was received between 22 Sept. 1997 and 21 Nov. 1998 while rainfall in October 2002 was about three times the long-term average for this month.

System Productivity

Cotton

In Year 1, more ($P < 0.05$) cotton was produced by the monoculture system than the integrated system, but this was reversed ($P < 0.06$) in Year 2 (Fig. 4; year × system interaction; $P < 0.09$). No differences were observed in other years. Higher yields in both systems in Year 1 were attributed to responses from cultivating land previously in long-term grass production and were probably related to increased decomposition rates of organic matter with mineralization of nutrients due to soil disturbance. Yields among years were relatively similar across the following 4 yr. Fiber quality did not differ ($P > 0.05$) between the two systems (data not shown).

Averaged across the four production years following the initial establishment year, cotton lint yield did not differ ($P > 0.05$) and was 1036 and 1062 kg ha^{-1} (SE = 29) for continuous cotton and the integrated system, respectively. Both systems exhibited yields that were above average for the area. In Lubbock County, mean yield of irrigated cotton (mean of all irrigation types) was 550 kg lint ha^{-1} for this same 5-yr period (TASS, 1998–2002). Paymaster 2326RR is no longer considered to be among the highest-yielding varieties (Gannaway et al., 2001–2002) but was widely grown in this area at the time this research began.

In Year 5, a hailstorm on 4 June 2002 damaged cotton in the monoculture system beyond the point of expected
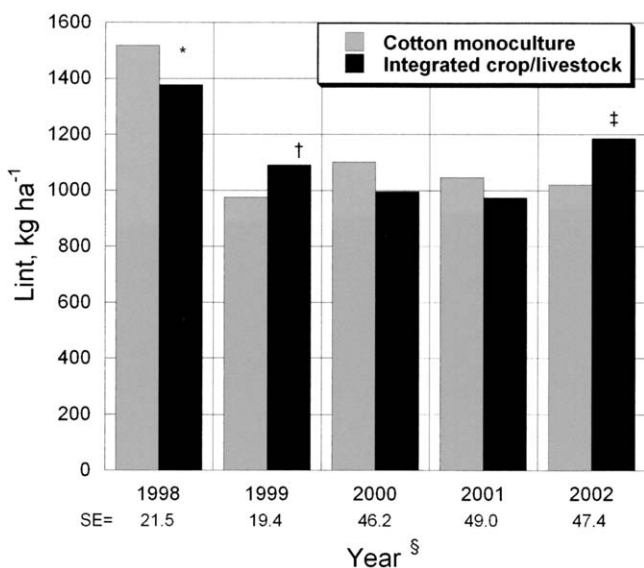

Fig. 4. Total annual yield of cotton during 5 yr for a cultivated cotton monoculture and no-till cotton grown in a two-paddock rotation with rye and wheat within an integrated cotton–forage–livestock system. *Indicates difference between systems within a year ($P < 0.05$). †Indicates difference between systems within a year ($P < 0.06$). ‡Indicates difference between systems within a year ($P < 0.14$). §Year × system interaction ($P < 0.09$).

recovery while the integrated system cotton survived the hailstorm with more plants intact. Although both systems included small-grain residues for ground cover, planting cotton into raised beds in the continuous system with wheat residue in furrow bottoms between beds appeared less effective in providing protection than no-till planting cotton directly into rye residue with no raised beds. Plant counts recorded on 30 May 2002 indicated stands of 120 900 and 92 500 plants ha^{-1} for the monoculture cotton and the integrated cotton–livestock system, respectively. Optimum stands for this region range from 86 500 to 123 600 plants ha^{-1} (Boman and Leser, 2003). On 14 June 2002, 10 d after the hail event, plant stands were 27 200 and 49 400 plants ha^{-1} for the cotton monoculture and the cotton component of the integrated cotton–livestock system, respectively. While 49 400 plants ha^{-1} would be considered marginal, 27 200 plants ha^{-1} would not be considered a viable stand, and replanting would be recommended (Boman and Leser, 2003). The decision was made, however, to maintain both stands to determine effects of planting technique or degree of ground cover on resistance to hail damage. Plants in both systems recovered, and by harvest, there was only a trend ($P < 0.14$) for higher yield by the integrated crop–livestock system, and total yields for both systems were similar to the past 3 yr.

Old World Bluestem Seed

Averaged across the four production years, yield was 21.1 kg PLS ha^{-1}, but seed yield differed by year (range 0 to 50.6 kg PLS ha^{-1}). A seed harvest (7.8 kg PLS ha^{-1}) was obtained in the year of establishment (1998), but yield was lower than the following year (50.6 kg PLS ha^{-1}). No seed were harvested during 2000. Lack of rainfall during the growing season diverted limited water available for irrigation to the cotton crops in each system, delaying the time that irrigation began on bluestem in late summer of 2000. Delayed growth of grass resulted in seed development that did not reach a harvestable stage before freezing weather. In Year 4 and 5, seed yields were about one-half yield harvested in Year 2. In Year 5, part of the seed crop was lost due to wind and rain that caused shattering of seed and are thus not accounted for in the yield. In all years, some seed loss from shattering was observed due to wind. Mean seed quality for Dahl old world bluestem was 35.8% PLS for the 4 yr with measurable yield. Quality of seed also varied by year, ranging from 18.3% (Year 4) to 44% PLS (Year 5).

More research is needed to optimize yield and quality of seed, including effects of grazing, fertilization, and timing and amount of irrigation. As managed in this system, grazing until mid-July did not preclude a seed harvest in October. Dahl bluestem differs from other commonly used old world bluestems in that it begins stem elongation later in the growing season and produces only one crop of seed. Recent observations suggest that Dahl bluestem suppresses populations of red imported fire ant (*Solenopis invicta* Buren; Hymenoptera; Formicidea; Britton et al., 2002). If conclusive evi-
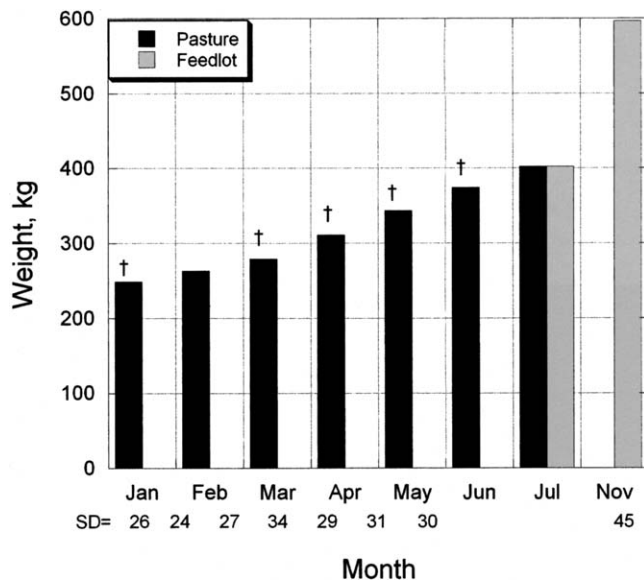
Fig. 5. Performance of steers sequence grazing WW-B. Dahl old world bluestem, rye, and wheat from January to mid-July in a three-paddock integrated cotton–forage–livestock system followed by finishing in the feedyard from mid-July to Nov. †Indicates effect of year ($P < 0.05$).

Fig. 6. Total days that WW-B. Dahl old world bluestem (OWB), rye, and wheat were grazed by month in a three-paddock integrated cotton–forage–livestock system. †In one year only, steers began grazing in December.

dence for this is found, along with value of this forage for grazing, seed production could become more profitable.

Cattle and Forages

Daily gains of stocker steers averaged 0.82 kg, and gains were similar during each of the 4 yr (Fig. 5). Steers averaged 402 kg (SD = 30 kg) at the end of the grazing season for a total gain of 153 kg while on pasture. Steers averaged 192 d on pasture and 125 d in the feedyard. Final weights of steers at harvest averaged 597 kg (SD = 45 kg) with 54% of carcasses grading USDA Choice. Performance during the finishing phase was similar in all 4 yr, and gains were typical of those expected by commercial feeders (M. Dettle, Coldwater Creek Cattle Co., Stratford, TX, personal communication, 2004).

In January, when steers entered the system, they began grazing autumn-accumulated (stockpiled) old world bluestem (Fig. 6) and were supplemented with cottonseed cake. Total annual CP supplementation was 34 kg steer^{-1}. As growth of rye permitted, steers sequentially grazed rye in combination with bluestem beginning 1 d per week and increasing in days until rye was terminated in April, by which time wheat was ready for grazing. Once wheat grazing began, only a few days of grazing occurred on bluestem paddocks until wheat was grazed out. Total grazing days for rye, wheat, and old world bluestem averaged 33.5, 25.3, and 122 d, respectively. Because there was more area in the old world bluestem paddock than in small-grain paddocks, numbers of grazing days per hectare were calculated. Old world bluestem provided about twice the number of steer grazing days per hectare (410 d ha^{-1}) than either rye (252 d ha^{-1}) or wheat (190 d ha^{-1}).

Sequencing rye, cotton, wheat, fallow, and rye provided continuity of grazing days. Because rye followed a fallow period, planting could be made at the optimum
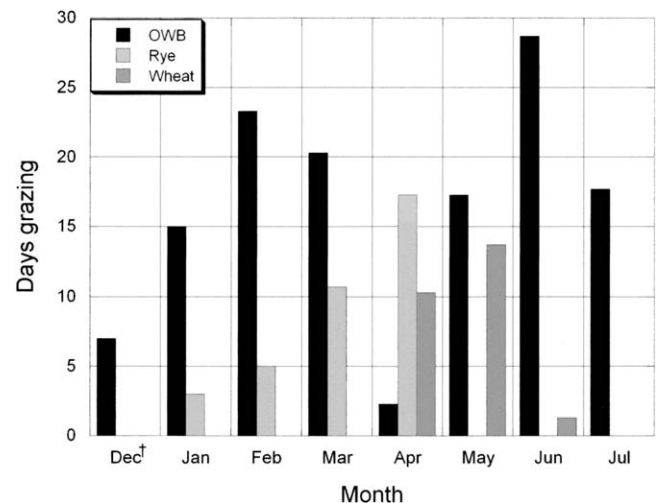
time for fall and winter growth when a high quality complimentary forage was needed. Rye was preferred to wheat for early planting due to greater winter growth potential as well as earlier maturity in spring to provide the cover crop for no-till planting of cotton. Wheat planted after cotton provided little winter growth but was ready for grazing by the time rye grazing was completed. Wheat grows later into the spring than rye and because it was followed by a fallow period, there was no time constraint to complete grazing of wheat. Sorghum, initially included in the rotation, was discontinued after Year 1. It was obvious in this year that there were neither sufficient days for growing nor irrigation water available to include sorghum in the rotation.

During the first year that steers were in the system, steers were removed from pasture and supplemented with hay if precipitation and wet soils endangered newly established bluestem pastures. After the initial year of grazing, no supplemental feed was required (other than CP supplement described above), and steers remained on pastures continuously from the time grazing began in January until they were transported to the feedyard in July.

Water Use

Because Year 1 was unique due to establishment of crops, adjustments in irrigation and cropping systems, absence of cattle, and actual duration (more than 12 mo), it is reported separately. Unusually dry weather and high temperatures during the establishment year (1998) required more irrigation water for all crops than would be expected normally. Irrigation water applied to the monoculture cotton system was 127 and 617 mm for terminated wheat and cotton, respectively. The integrated system required 1146, 439, 406, 483, and 394 mm for each crop component to establish old world bluestem and grow the first crop of cotton, wheat, rye, and sorghum. Old world bluestem can be established under dryland conditions in this environment, but the unusu-

ally dry year and need to ensure stands to begin research resulted in a high use of irrigation water. Thus, more water was required by the integrated system during the establishment year than the cotton monoculture (1029 vs. 744 mm, respectively). Sorghum was discontinued after Year 1. Additional water used by the integrated system was due in part to water applied to sorghum in the first year and was one reason for discontinuing this part of the rotation.

Averaged across Years 2 through 5, irrigation water applied was 481 mm to the monoculture cotton system while the integrated cotton–livestock system received 372 mm (SE = 7). Thus, after the establishment year, the monoculture cotton system used 23% more ($P <$ 0.01) water per hectare annually than the integrated crop–livestock system. Lower water use by the integrated system was due largely to water use efficiency of the warm-season perennial grass, which represented about half of the land area within this system. Warm-season C_4 grasses are generally more water use efficient (Hopkins, 1995) with a lower transpiration ratio (Martin et al., 1976) than cool-season C_3 species such as wheat and rye.

Water applied to crops reflected precipitation distribution as well as differences in water use efficiency among plant species, and total water applied per hectare differed among crop components within the two systems. Total water applied to old world bluestem averaged across the 4 yr of grazing was 270 mm. This water was allocated across the growing season to supplement precipitation as needed to ensure forage for grazing by steers (Fig. 7). Generally higher precipitation in June (Fig. 2 and 7) reduced irrigation requirements during this period. Once steers were removed from pastures in mid-July, irrigation was limited to that required to prevent dormancy. Irrigation water was increased in August and September to promote seed production and to stockpile forage for winter grazing by steers. From April through October, about 57% of ET_o was replaced by irrigation plus precipitation.

Within the integrated system, rye required more ($P <$ 0.05) water than wheat (290 vs. 172 mm, respectively). Although September is typically one of the wettest months, less than one-half of expected precipitation occurred during the years of this experiment, and rye planted in September required water applied for germination and early growth. Furthermore, most growth of rye occurred during January through March, a time when precipitation is low typically (Fig. 2). Wheat, planted in November when temperatures were cooler, did not require as much irrigation for germination, and most growth of this forage occurred during the season when precipitation generally was increasing (April to June). Although total irrigation water applied was similar between bluestem and rye, there were nearly twice the steer grazing days per hectare per centimeter of water applied to Dahl bluestem (15 d ha^{-1} cm^{-1}) than was achieved with rye (9 d ha^{-1} cm^{-1}). Wheat provided the lowest number of steer grazing days per hectare but was similar to bluestem in number of steer grazing days per hectare per centimeter of irrigation water applied
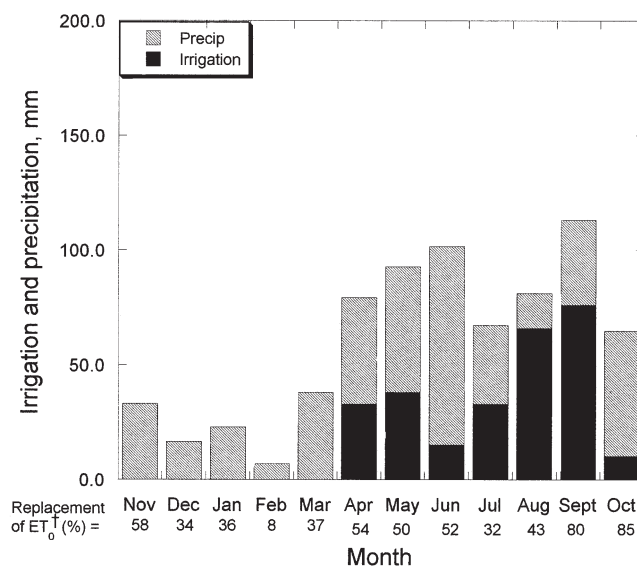

Fig. 7. Total water (precipitation plus subsurface drip irrigation) applied by month to WW-B. Dahl old world bluestem grazed by steers from January to mid-July and harvested for seed in October. †ET_o = reference crop evapotranspiration (mean of Years 2–5).

(15 d ha^{-1} cm^{-1}). Lower irrigation requirements for wheat as discussed above appeared to account for higher grazing days per hectare per centimeter of water applied.

Averaged across the four production years, water use per hectare by cotton in the integrated system was greater ($P < 0.05$) than that used by cotton in the monoculture system (516 vs. 419 mm, respectively; SE = 11 mm). Planting cotton flat into terminated rye should not require more water than planting into raised beds. More water was applied in May in the integrated system than was required in an effort to wet soils across a wider area to stimulate germination due to imprecise placement of seed directly over drip tapes. In midsummer, due to limitations in flexibility restricting fertilizer injection application, differences in actual field size, and demands on the irrigation system by other research projects, more water was required by the integrated system to apply similar N fertilizer amounts during a similar time period for both systems. Added water did not appear to contribute to productivity, and water was probably overapplied. This additional irrigation water could be eliminated by resolving these mechanical problems.

Total water supply (precipitation plus irrigation) increased to a maximum in July as demands of cotton growth increased for both systems (Fig. 8). Replacement of ET_o averaged 65 and 77% for monoculture cotton and the integrated system cotton, respectively. When cotton was planted in 1998, soil moisture averaged about 74 and 63% of field capacity in the continuous and integrated systems, respectively, while in 2001, soil moisture was 57% of field capacity in both systems. Bordovsky and Porter (2003) suggested that 80% of field capacity for an Olton soil (fine, mixed, thermic Aridic Paleustolls) represented a "full" preplant soil water scenario and that under these conditions, at least 47% of total water was lost before planting when irrigated at 2.5 mm d^{-1} pumping capacity regardless of irrigation delivery system.
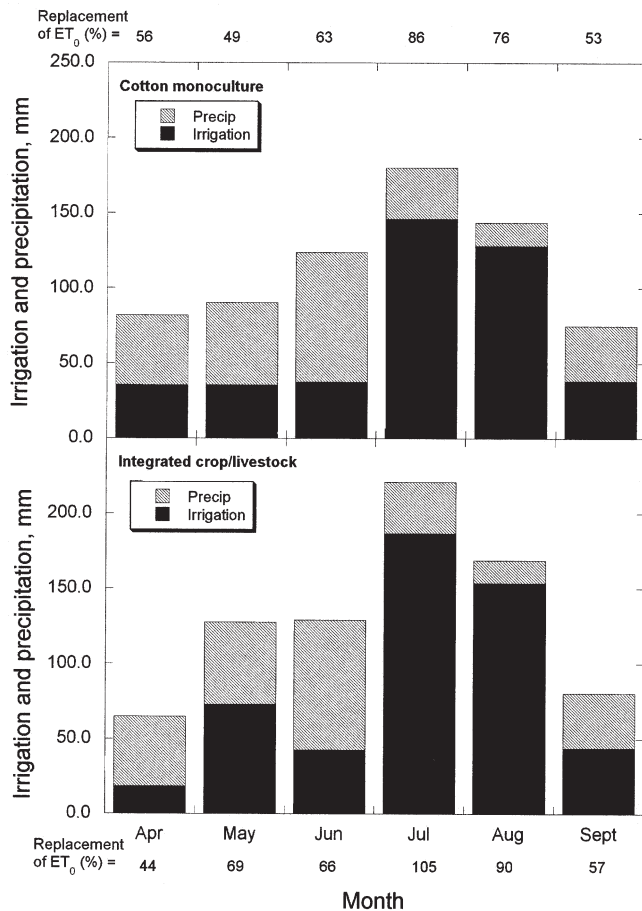
Fig. 8. Total water (precipitation plus subsurface drip irrigation) applied to cotton during the growing season and percentage replacement of reference crop evapotranspiration (ET$_o$) by month (mean of Years 2–5).

Fertilizer and Chemical Inputs

Chemicals, including herbicides, pesticides, and plant growth regulators, required for cotton production per se were generally similar between the two systems if compared on a per-hectare basis for that crop alone (Table 1). Because cotton in the integrated system represented only 23.2% of the total area, the overall system chemical inputs were lower than for the cotton monoculture. In the first year of this experiment, trifluralin [2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl)benzenamine] was applied preplant incorporated in conventional cotton to control annual grass and small-seeded broadleaf weeds. In the integrated cotton system, S-metolachlor {2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide} and prometryn [N,N'-bis (1-methyl-ethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine] were used pre-emergence rather than trifluralin because these herbicides do not require mechanical incorporation and provide broad-spectrum weed control. After the first year, weed control in the conventional cotton system was achieved by trifluralin and glyphosate whereas weed control in the integrated system was achieved by glyphosate applications in cotton and dicamba (dimethylamine salt of 3,6-dichloro-o-anisic acid) spot spraying in noncotton years when wheat was grown in these paddocks.

Nitrogen fertilizer applied was about 40% lower in the integrated cotton–livestock system than in monoculture cotton. This represents not only a lower economic cost but also a lower energy input as well. Manufacture of N fertilizer is an energy expensive process (Whitehead, 1995). During the four production years, total N applied to cotton in the monoculture and to cotton in the integrated system was 140 and 143 kg ha^{-1}, respectively, or about 0.23 and 0.21 kg N mm^{-1} total water applied (irrigation plus precipitation during the 120-d growing season). Morrow and Krieg (1990) suggested that within any heat unit regime, lint yield was maximized as water supply increased by maintaining a constant ratio of 0.2 to 0.25 kg N ha^{-1} mm^{-1} water in the environment of the Texas High Plains. Thus, rates of N application to cotton in the current experiment were within levels suggested to maximize yield at irrigation levels used plus precipitation that occurred at this site.

Chemical inputs to small grains included N fertilizer and glyphosate to terminate wheat after grazing and rye for no-till planting of cotton in the integrated cotton–livestock system and to terminate wheat before cotton in the monoculture cotton system. Dicamba was applied to suppress weeds following graze-out of wheat in the integrated system and in terminated wheat in the monoculture system (Table 1). Following establishment, the perennial warm-season grass pasture has required no input of chemical other than N fertilizer. No fertilizers for any crop other than N were indicated based on soil test analyses at establishment or during the first 5 yr of this experiment.

Soil-Borne Diseases

Soil-borne disease potential was close to zero at the beginning of this research. *Verticillium dahliae* Kleb.

Wheat terminated before cotton planting in the cotton monoculture system received an average of 83 mm of water during the 3 yr that wheat was grown. In 1 of the 4 yr following establishment, weather and timing prevented establishment of wheat in this system. This practice is recommended to reduce erosion of soil, primarily by wind, and is practiced mostly on coarse-textured soils with a center-pivot irrigation system (about 100 000 ha in the High Plains, W. Keeling, personal communication, 2004). To meet the definition of a sustainable resource management system, the erosion rate should not exceed 11.2 Mg ha^{-1} yr^{-1}, and this practice would thus be recommended for some soils. Predicted wind erosion at the site using the Universal Wind Erosion Equation (Fryrear et al., 2001) suggested that estimated soil loss in the continuous cotton system exceeded 10 Mg ha^{-1} yr^{-1} but was less than 7 Mg ha^{-1} yr^{-1} from the cotton component of the integrated system (Collins, 2003). Collins (2003) found that including estimates of soil loss by water erosion increased estimated losses to more than 19 Mg ha^{-1} yr^{-1} for monoculture cotton but had little effect on soil loss from the cotton component in the integrated system. Predicted soil loss from pastures in the integrated system was less than 0.5 Mg ha^{-1} yr^{-1} by either estimation (Collins, 2003).

population was <1 colony-forming unit cm^{-3} soil for all treatments, which is low for disease development in cotton. No wilt symptoms were observed in any growing season in cotton in either system. No damaging plant parasitic nematodes on cotton (Koenning et al., 2004) were ever identified at this site. Use of a bioassay to bait for seedling disease showed little disease initially, even in absence of seed treated with fungicides. Seedling disease potential in the absence of fungicides increased with time with the monoculture cotton though not significantly. However, cotton seedling disease under conducive environmental conditions was always prevented with a standard fungicide seed treatment of triadimenol [β-(4-chlorophenoxy)-α-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol] plus mefenoxam [methyl *N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl)-D-alaninate] plus thiram (tetramethylthioperoxydicarbonic diamide). Stand differences in the field were inconsistent only in the presence of hail or weed pressure, and seedling roots were mostly clean of lesions. Root necrosis and hypocotyl ratings from field plants indicated almost no seedling disease present in any cotton treatments.

Weed Populations and Control

Weed control in cotton was challenging because of the inherited seed bank of annual weeds, particularly Palmer amaranth (*Amaranthus palmeri* S. Wats.), and the population of difficult-to-control perennial weeds such as field bindweed (*Convolvulus arvensis* L.) and silverleaf nightshade (*Solanum elaeagnifolium* Cav.). Palmer amaranth was controlled by glyphosate applied when cotton was at the four-leaf stage followed by an additional application postemergence-directed. However, weed escapes and continuous Palmer amaranth were common. Perennial weeds were suppressed by these glyphosate applications, but season-long control was difficult to accomplish. Field bindweed was the dominant weed at this location, and none of the glyphosate treatments provided satisfactory control. Although cattle were observed to graze weeds, as managed in the integrated system, grazing did not appear to reduce weed presence in the following cotton crop.

Economic Analysis

Like any other multiyear-type analysis, given that the 1997–1998 crop year was the initial year of the project

and stocker cattle were not present during this year, resulting costs and return budgets must be evaluated with caution. However, accounting of the systems' establishment costs need to be documented and considered in the overall annual profitability evaluation for the crop production systems in the long run.

Establishment Year

For the establishment year, projected net returns above variable costs of production per hectare of the monoculture cotton system, which included terminated wheat, for 45-, 60-, 75-, and 90-m pumping lift scenarios were $756.62, $698.70, $635.71, and $572.73, respectively. The projected proportional per-hectare net returns above variable costs of production for the integrated crop–livestock system that included cotton and rye hay production (23.2% of total area), wheat and sorghum hay (23.2% of total area), and establishment of WW-B. Dahl old world bluestem permanent pasture (53.6% of total area) for 45-, 60-, 75-, and 90-m pumping lift scenarios were $209.81, $131.85, $47.05, and −$37.76, respectively.

Years 2 through 5

Following the establishment year, 4 yr have been completed that include cattle in the system. Net returns above variable costs of production for these 4 yr are given in Table 2. Averaged across these years, the integrated system has proven to be more profitable than the conventional cotton system at every pumping depth with difference becoming greater as depth to water increases. Under conditions of this experiment and with prices used, this represented a 90% increase in profitability for the integrated system at the 90-m pumping depth that occurred at the research site. This is important because greater water table depth simulates greater water scarcity. Therefore, the more scarce the water, the greater the justification to adopt the integrated production system. It is important to highlight that of the 4 yr included in calculations in Table 2, these include 1 yr in which no bluestem seed were harvested.

DISCUSSION

Worldwide, issues concerning water are escalating. About 97.5% of the total water on earth is in oceans and is saline with most of the remaining 2.5% nonsaline

Table 2. Net returns above variable costs of production of a cotton monoculture system and an integrated cotton–forage–livestock system averaged over Years 2 through 5.†

	Net returns per hectare for two systems	
Irrigation water pumping lift	Monoculture cotton‡	Integrated cotton–forage–livestock‡§¶
m	net returns above variable cost of production, $ ha^{-1}	
45	310.38	453.33
60	272.75	424.62
75	231.83	393.41
90#	190.91	362.17

† Returns do not include any government payments due to variability of benefits received by producers.
‡ Price used for cotton lint was $1.21 kg^{-1}.
§ Price used for old world bluestem seed was $39.60 kg^{-1}.
¶ Price used for steers was $1.92 kg^{-1}.
# Actual pumping lift at the research site.

water contained in icecaps of Greenland and Antarctica (USDA Forest Serv., 2000). Less than 1% is fresh water that is accessible in surface and ground water reservoirs, and much of the water in underground aquifers is both old and slow to recharge. The Ogallala aquifer is such a source with most references dating its origin to about 10 million years ago (Kromm and White, 1992). The Ogallala is the major water-bearing unit of the Texas High Plains (Weeks and Gutentag, 1984). Water withdrawn for irrigation has enabled this region to become one of the largest areas of intensive agricultural production on earth. More than 95% of water withdrawn from the Ogallala in the Southern High Plains is used for irrigation (Gutentag et al., 1984; LERWPG, 2001), which accounts for more than 70% of crop revenues from irrigated agriculture (Arabiyat et al., 1999). Water has been withdrawn from the Ogallala at rates that have exceeded recharge for many years. For the 15 counties around Lubbock, TX, the water level dropped an average of 399 mm yr^{-1} from 1993 to 2003 (High Plains Underground Water Conservation District No. 1, 2003). Recharge of the aquifer primarily depends on precipitation. With the low rainfall and high evapotranspiration (5.5 times precipitation) typical of this region, the amount of recharge is estimated to range from only a few millimeters to a maximum of 25 to 50 mm yr^{-1} (Gutentag et al., 1984; High Plains Underground Water District, personal communication). Thus, current rates of water withdrawal are not sustainable.

During the past 20 yr, improvements in both surface and subsurface irrigation technologies have replaced many more wasteful irrigation systems. Use of subsurface drip irrigation is expanding in the Texas High Plains and has often, but not always, resulted in increased cotton yields (Bordovsky and Porter, 2003). Increased cotton lint yield and water use efficiencies, compared with surface application by low-energy precision application (LEPA) or spray technology, appears due to higher water losses from surface evaporation with LEPA irrigation (Bordovsky and Porter, 2003). In the current research, subsurface irrigation allowed more precise timing of water application and avoided mechanical challenges of surface systems with fencing and livestock.

The combined annual economic value of the crops and livestock in this region exceeds $5.6 billion ($1.1 billion for crops; $4.5 billion livestock; TASS, 2002) but is highly dependent on water from the Ogallala aquifer. The future for this region will not be a continuation of past practices. Water in sufficient quantities will not be available to support irrigation practices and cropping systems that came to characterize this region during the last century. If the economy and productivity of this region are to be sustained into the future, new practices and agricultural systems that are less consumptive of natural resources are essential. If limited water available for irrigation forces cropping systems dependent on that water to shift to higher-rainfall regions, the impact on local and regional economies will be large. Furthermore, loss of agricultural lands to urban expansion and increasing population pressures in these higher-rainfall areas

is limiting and even excluding the potential for such a shift to occur.

Cutforth et al. (2001) suggested that diversity was the foundation of sustainable cropping systems to reduce risks of pest and disease outbreaks and impacts of agrichemicals. Historically, U.S. farming systems in general were diverse and integrated through feeding of forage crops and crop residues to livestock with manures used as a nutrient source for crops, but today, plant and animal production have been almost entirely separated (Hardesty and Tiedeman, 1996). This is the case in the Texas High Plains where little integration of cotton and livestock production exists. Today, impacts on environmental quality, pest management, diminishing natural resources, and issues of biosecurity have reawakened interest in more diversified agriculture and landscapes.

Thus far in our research, no benefits in cotton yields have been measured due to rotation with forages, but soil (0 to 5 cm) microbial biomass C and N and enzyme activities were enhanced in perennial pastures and in the rotation depending on crop sampled compared with cotton grown in monoculture (Acosta-Martínez et al., 2004). Collins (2003) demonstrated lower soil erosion potential for the integrated system than for monoculture cotton within the current research. Furthermore, no-till planting cotton into rye stubble after grazing by cattle provided more protection to young cotton plants from hail and blowing sand experienced in 2002, and more plants survived than in the monoculture system. Additional differences between the two systems may be present in terms of total energy consumed, potential for wildlife habit, and contributions to recreational opportunities and open space. These and other measures of environmental impact are being evaluated within our ongoing investigations.

Cook et al. (2003) demonstrated that yield of cotton lint within a given physical environment and water supply differed among varieties of cotton. In their studies, yield response of numbers of cotton cultivars to a wide range of water supplies was investigated during 7 yr. Kilograms of lint per millimeter of water were strongly affected by environment, differing nearly twofold from year to year. Based on this long-term study, they concluded that physical environment dictates water use efficiency of cotton, but genetic differences in water use efficiency exist although they are relatively small. During the 7 yr of their study, cotton lint yield ranged from less than 250 to more than 2000 kg ha^{-1} and increased as total water supply increased. Water use efficiency ranged from 1.2 to 2.4 kg lint mm^{-1} water with irrigation use efficiency paralleling total water use efficiency. Irrigation use efficiency ranged from 2.2 to 3.8 kg lint mm^{-1}. In the present study, irrigation use efficiency was 2.5 and 2.1 kg lint mm^{-1} for the cotton monoculture and cotton in the integrated system, respectively.

Bordovsky and Porter (2003) reported lint yields of 1.35 Mg ha^{-1} using Paymaster 2326RR with drip irrigation, a full preplant soil moisture scenario, 340 mm of total irrigation, and an irrigation capacity of 5.1 mm d^{-1}, an irrigation capacity common for well-irrigated cotton on the Southern High Plains. They also reported that

with limited preplant soil moisture, 260 mm of total irrigation, and an irrigation capacity of 2.5 mm d^{-1} (a deficit irrigation rate of less than one-third peak evapotranspiration rate of cotton), 1.01 Mg lint ha^{-1} was produced, suggesting that with refinements in management, further water saving can be achieved with little impact on yield.

Forage crops in the integrated system used 252 mm ha^{-1} irrigation water, similar to the most efficient system for cotton reported by Bordovsky and Porter (2003), but these levels still exceed recharge potential for the aquifer. As further improvements in management techniques for both cotton and forages crops are found and combined with improved genetics for yield and water use efficiencies, further water-saving strategies will be developed and must be tested. Results of our research are a step toward finding more sustainable agricultural practices for this region that address both economic viability and protection of natural resources including water. If the difference in water use achieved by improved plant and animal management strategies is retained in the aquifer, progress would be made in conserving water. However, if the water saved is then used to irrigate additional land area, profitability in the short term can be increased considerably, but there would be no savings in water. Recent adoption of water-conserving irrigation technologies has allowed additional lands to be irrigated using the water savings made possible by the more efficient systems, but with additional wells withdrawing water, the aquifer has continued to decline (Segarra and Feng, 1994). Krall and Schuman (1996) suggested that while integrated dryland crop and livestock production systems could be both profitable and sustainable in the Great Plains, tradition and managerial experience might slow adoption. This will likely affect adoption of practices in the Texas High Plains, but opportunities exist to convert more marginal lands into forage and livestock production while continuing to use better land and water resources for crop production.

Finally, systems are site specific and reflect unique combinations of resources and management objectives of producers. We have examined only one possible alternative system to the cotton monoculture. Results of our research indicated that combining cotton and grazed forages within a system was more profitable and used less water and chemicals than a cotton monoculture. Diversification provided three harvestable crops (cotton, cattle, and grass seed) compared with the single crop in the cotton monoculture. Flexibility of the integrated system could allow harvesting forage for hay and wheat and rye for grain if changes in commodity prices made these choices favorable. Economically, however, the small-grain component of the integrated system was the least cost effective. Systems based on all perennial forages should be tested to avoid costs associated with these annual forages. Further research is urgently needed to test systems that do not require irrigation or that further reduce the need for irrigation to reach sustainable levels of water use in the Texas High Plains.

REFERENCES

Acosta-Martínez, V., T.M. Zobeck, and V. Allen. 2004. Soil microbial, chemical, and physical properties in continuous cotton and integrated crop–livestock systems. Soil Sci. Soc. Am. J. 68:1875–1884.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. FAO Irrig. and Drainage Paper 56. FAO, Rome.

Arabiyat, T.S., E. Segarra, and D.B. Willis. 1999. Sophisticated irrigation technology and biotechnology adoption: Impacts on ground water conservation. AgBioForum 2(2):132–136.

Boman, R., and J. Leser. 2003. Management of late cotton in 2003 [Online]. Available at http://lubbock.tamu.edu/cotton/pdf/managementoflatecotton.pdf (verified 3 Nov. 2004). Texas Coop. Ext., Texas A&M Univ., Lubbock.

Bordovsky, J.P., and D. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA and subsurface drip irrigation. ASAE Paper no. 032008. 2003 ASAE Annu. Int. Meeting, Las Vegas, NV. ASAE, St. Joseph, MI.

Britton, C., G. Perry, C. Villalobos, R. Kellison, C. Craig, H. Thorvilson, V. Allen, and B. Racher. 2002. Red imported fire ants and WW-B.Dahl: Preliminary observations. Res. Highlights—2002 33:22.

Brooks, E., J. Emel, B. Jokisch, and P. Robbins. 2000. The Llano Estacado of the US Southern High Plains: Environmental transformation and the prospect for sustainability. United Nations Univ. Press, New York.

Collins, J. 2003. Agricultural phosphorus in an integrated crop/livestock system in the Texas High Plains. M.S. thesis. Texas Tech Univ., Lubbock.

Cook, R., D. Krieg, and W. Ralston. 2003. Genetic variability for water use efficiency. p. 1689–1691. In Proc. Beltwide Cotton Conf., Nashville, TN. 6–10 Jan. 2003. Natl. Cotton Counc. of Am., Memphis, TN.

Cutforth, L.B., C.A. Francis, G.D. Lynne, D.A. Mortensen, and K.M. Eskridge. 2001. Factors affecting farmers' crop diversity decisions: An integrated approach. Am. J. Alternative Agric. 16:168–176.

Donald, C.M. 1981. Innovation in Australian agriculture. p. 57–86. In D.G. Williams (ed.) Agriculture in the Australian economy. Sydney Univ. Press, Sydney, Australia.

EWRI. 2001. The ASCE Standardized Reference Evapotranspiration Equation [Online]. Available at http://www.kimberly.uidaho.edu/water/asceewri/main.pdf (verified 3 Nov. 2004). EWRI of ASCE, Reston, VA.

Fryrear, D.W., P.L. Sutherland, G. Davis, G. Hardee, and M. Dollar. 2001. Wind erosion estimates with RWEQ and WEQ. p. 760–765. In D.E. Stott, R.H. Mohtar, and G.C. Steinhardt (ed.) Sustaining the global farm. Proc. Int. Soil Conserv. Org. Meeting, 10th, Purdue Univ., West Lafayette, IN. 25 May 1999. Int. Soil Conserv. Org., USDA-ARS Natl. Soil Erosion Res. Lab., and Purdue Univ., West Lafayette, IN.

Gannaway, J.R., T.A. Wheeler, R.K. Bowman, M. Murphy, D. Nes-

mith, L. Schoenhals, and V. Morgan. 2001. Cotton performance tests in the Texas High Plains and Trans-Pecos areas of Texas 2001. Tech. Rep. 02–1. Texas Agric. Exp. Stn., Lubbock.

Gannaway, J.R., T.A. Wheeler, R.K. Bowman, M. Murphy, D. Nesmith, L. Schoenhals, and V. Morgan. 2002. Cotton performance tests in the Texas High Plains and Trans-Pecos areas of Texas 2002. Tech. Rep. 03–1. Texas Agric. Exp. Stn., Lubbock.

Gutentag, E.D., F.J. Helmes, N.C. Krothe, R.R. Lucky, and J.B. Weeks. 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. USGS Professional Paper 1400-B. U.S. Gov. Print. Office, Washington, DC.

Hardesty, L.H., and J.A. Tiedeman. 1996. Integrating crop and livestock production in inland Northwest farming systems. Am. J. Alternative Agric. 11:121–126.

High Plains Underground Water Conservation District No. 1. 2003. Depth-to-water level measurements in district observation well network reveal average ground water level decline of 1.06 feet during 2002. The Cross Section 49(4):1.

Hopkins, W.G. 1995. Photosynthesis: Carbon metabolism. p. 203. *In* Introduction to plant physiology. John Wiley & Sons, New York.

Koenning, S.R., T.L. Kirkpatrick, J.L. Starr, J.A. Wrather, N.R. Walker, and J.D. Mueller. 2004. Plant parasitic nematodes attacking cotton in the United States: Old and emerging production challenges. Plant Dis. 88:100–113.

Krall, J.M., and G.E. Schuman. 1996. Integrated dryland crop and livestock production systems on the Great Plains: Extent and outlook. J. Prod. Agric. 9:187–191.

Kromm, D.E., and S.E. White. 1992. The High Plains Ogallala Region. *In* D.E. Kromm and S.E. White (ed.) Ground water exploitation in the High Plains. Univ. Press of Kansas, Lawrence.

Llano Estacado Regional Water Planning Group. 2001. Executive summary. p. ES-21. *In* Llano Estacado regional water planning area regional water plan. HDR Eng., Inc., Austin, TX.

Luna, J., V. Allen, J. Fontenot, L. Daniels, D. Vaughan, S. Hagood, D. Taylor, and C. Laub. 1994. Whole farm systems research: An integrated crop and livestock systems comparison study. Am. J. Alternative Agric. 9:57–63.

Martin, J.H., W.H. Leonard, and D.C. Stamp. 1976. Principles of field crop production. MacMillian Publ. Co., Inc., New York.

Morrow, M.R., and D.R. Krieg. 1990. Cotton management strategies for a short growing season environment: Water-nitrogen considerations. Agron. J. 82:52–56.

National Reseach Council. 1996. Nutrient requirements of beef cattle. 7th ed. Natl. Academy Press, Washington, DC.

Segarra, E., and Y. Feng. 1994. Irrigation technology adoption in the Texas High Plains. Tex. J. Agric. Nat. Resour. 7(1):71–83.

Steel, R.G.D., and J.H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill Book Company, Inc., New York.

[TASS] Texas Agricultural Statistics Service. 1998–2002. Texas agricultural Statistics. TASS, Austin, TX.

Thistlethwayte, B. 1970. Reproduction of *Pratylenchus penetrans* (Nematoda: Tylenchida). J. Nematol. 2:101–105.

USDA Forest Service. 2000. Water and the Forest Service. FS-660. USDA Forest Serv., Washington, DC.

USDA National Agricultural Statistics Service. 2003. 2003 Agricultural statistics. U.S. Gov. Printing Office, Washington, DC.

Weeks, J.B., and E. Gutentag. 1984. The High Plains Regional Aquifer—geohydrology. p. 6–25. *In* G.A. Whetstone (ed.) Proc. Ogallala Aquifer Symp., II. June 1984. Water Resour. Cent., Texas Tech Univ., Lubbock.

Wheeler, T.A., K.D. Hake, and J.K. Dever. 2000. Survey of *Melidogyne incognita* and *Thielaviopsis basicola*: Their impact on cotton fruiting and producers' management choices in infested fields. J. Nematol. 32(Suppl. 4S):576–583.

Wheeler, T.A., and R.C. Rowe. 1995. Influence of soil characteristics and assay techniques on quantification of *Verticillium dahliae* in Ohio soils. Plant Dis. 79:29–34.

Whitehead, D.C. 1995. Grassland nitrogen. CAB Int., Biddles Ltd., Guildford, UK.